A BUOYANCY CONTROL SYSTEM

[001] The present invention relates to a buoyancy control system, and in particular to a buoyancy control system for controlling the buoyancy of an underwater submersible.

[002] Unmanned submersibles are used for studying the undersea environment. There are two principal types of such submersibles, remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs).

[003] ROVs are free swimming vehicles tethered to a ship via an umbilical cable link which supplies electrical power and/or telemetry to the ROV. ROVs are effectively used, for example, in the oil industry for sub-sea surveys and operations; however, since they require the constant presence of a surface vessel and crew, ROV running costs are high.

[004] Due to the high running costs of ROVs, they are increasingly being replaced with AUVs. One such type of AUV is a so-called "drifter", i.e. an AUV which uses buoyancy control to hold position within the water at predetermined depths to collect data. Having collected data, the drifter rises to the surface to transmit the data to a home station, and then resubmerges to record further data, for example at a different site.

[005] Another type of AUV is a so-called "lander", which lands on the seabed to collect data, and then rises to the surface to transmit the data to a home station. Other types of AUV are also known, for example powered unmanned submarine-type vessels. It is sometimes also necessary for the AUV to return to the surface to check its position using the GPS system. Thus, the precise course which the AUV takes, the mission profile, will vary according to the nature and manner by which the data is to be collected.

[006] However, a problem with existing AUVs is that of

"trim", i.e. buoyancy in water. Existing AUVs are designed to float with typically only a few kg (for example, 2 or 3 kg) of positive buoyancy, which reduces manoeuvrability forces, resulting in a longer mission time. In addition, whenever an instrument is either attached to or removed from the AUV, it must be manually re-trimmed, which consumes valuable ship time. Furthermore, if the AUV is required to drop off or pick up an object during the mission then buoyancy is affected, which can result in either a rapid rise to the surface or, worse, drop to the seabed. Indeed, AUV buoyancy may be affected by mere changes in seawater density, to the extent that the AUV may not be able to surface, and thus be recovered.

[007] In addition, a particular problem with AUV landers is the impact of the lander on the seabed. This impact can disturb the environment the lander is intended to record, which thus affords false readings. For example, the bow wave in front of a sinking lander can disperse superficial sediment on the surface of the seabed, which the lander may be intended to study, and the noise of the lander impact on the seabed may influence the behaviour of animals intended to be studied.

[008] A further problem with unmanned (and indeed manned) submersibles is that of buoyancy control at depth (for example, 3000m or greater), due to the pressure of seawater at such depths. There are two main types of known buoyancy control system in this case.

[009] The first type of buoyancy control system uses compressed air, which is conventionally used for buoyancy control on manned submarines. In these systems, buoyancy is decreased by filling ballast tanks with water, and buoyancy is increased by forcing the water from the tanks using compressed air. The disadvantages of compressed air systems

are firstly that they require large amounts of power (hence their use on large, high-power manned submarines), and secondly that they are only operable to depths of hundreds of metres. The use of compressed air at greater depths becomes inefficient and dangerous, due to the very high air pressures required.

[0010] The second type of buoyancy control system uses a closed loop oil pumping system. In these systems, oil is pumped to and from a flexible bag, to thereby increase and decrease the volume of the bag, and accordingly the buoyancy of the submersible. The advantages of oil pumping systems are that they require relatively little power, and hence can be used on smaller submersibles, and can operate at much greater depths than compressed air systems, for example 3000m or greater. However, the buoyancy change afforded by oil pumping systems is relatively small, for example less than 1kg.

[0011] A problem that arises more frequently with AUVs is the drain on the electrical power supply. It is often a design aim for an AUV to make it small and relatively light. This aim is therefore not met if a larger power supply is required. Consequently, it often necessary to make a compromise between the size (and weight) of the power supply and the size (and weight) of the AUV. The size of power supply that is selected can also place limits on the mission profile for the AUV. The compromise that is eventually made also has an impact on the buoyancy control system that is used in the AUV. Thus, in any system used for buoyancy control difficulties arise in providing sufficient electrical energy to drive the various controls and other electrically operated components without, on the other hand, loading the vehicle with excessive battery weight and volume. These problems are particularly relevant when the AUV must descend into deep waters greater than 2000 metres for example.

[0012] There is therefore a need to provide a buoyancy control system which places a reduced demand on the power supply so that either the weight of the AUV can be reduced or more flexibility is introduced for the mission profile.

[0013] It is therefore an object of the present invention to provide a buoyancy control system which uses the power supply in an energy efficient manner.

[0014] According to the present invention there is provided a buoyancy control system for controlling the buoyancy of an underwater submersible, the system comprising:-

a buoyancy chamber having a seawater inlet and a seawater outlet;

a power supply used to power at least one electrical component of the system; and

a hydraulic system for pumping seawater from the chamber through the outlet, the hydraulic system comprising a hydraulic pump and a pressure multiplier, the hydraulic pump for applying pressure to the pressure multiplier, and the pressure multiplier for increasing the pressure applied thereto by the hydraulic pump, and for applying the increased pressure to seawater from the chamber to thereby pump out the seawater.

[0015] Other advantages and features of the present invention are defined in the subsidiary claims.

[0016] An example of the present invention will now be described in detail with reference to the accompanying drawings, in which:-

[0017] Figure 1 is a schematic of a buoyancy control system embodying the present invention; and

[0018] Figure 2 shows estimates of the energy required to generate buoyancy at 3000 metres depth using a pre-pressurised air cylinder of differing volumes at 300 bar.

[0019] Referring to figure 1, the buoyancy control system

comprises a buoyancy chamber in the form of a sphere 5 which is hollow and contains an internal space 6. The sphere 5 may be, for example, a glass, steel or titanium sphere. The sphere 5 must have sufficient strength under the pressures that it will operate under and has a capacity in this embodiment which is large enough to provide a buoyancy change of 25kg or greater, for example up to 34kg. The sphere 5 is provided with a first input 5A, a second input 7A, and an outlet 11A. An expandable flexible bag 7 is provided in the internal space 6 of the sphere 5 and has an input which is connected to the second input 7A of the sphere.

[0020] A cylinder of gas 10 is provided adjacent the sphere 5, the gas being under a pressure GP. The cylinder 10 is connected by a line 8 to the second input 7A. An electrically controlled solenoid valve 9 is included in the line 8 to control flow of gas along the line.

[0021] A line 3 is provided which has an input 2 opening to the seawater surrounding the buoyancy control system. The line 3 is connected to the input 5A of the sphere 5 and includes an electrically controlled solenoid valve 4, to control flow of seawater along the line 3, and a variable load electrical generator 33 having a turbine (not shown) such that the generator 33 generates electricity during flow of seawater along the line 3 into the sphere 5.

[0022] A pressure multiplier, generally identified by numeral 34, is provided which comprises a two part cylinder and two part piston. The two part piston comprises a relatively larger diameter plate 25 at one end connected by a rod 22 to a relatively smaller diameter plate 20 at the other end. The two part cylinder is formed to have one end 24 with a relatively larger diameter (larger diameter cylinder) and hence volume 23, in which the larger diameter plate 25 can travel, and the other end 18 with a relatively

smaller diameter (smaller diameter cylinder) and hence volume 19, in which the smaller dimeter plate 20 can travel. As illustrated, the two plates are connected such that both plates can travel together from the extent of their leftward travel, as illustrated, to their rightward extent. Proximity switches 26 and 21 are provided to detect the leftward and rightward extent of the large plate 25.

[0023] A hydraulic pump 28 is connected by a line 27 to the leftward end of the larger diameter cylinder 24 whilst an outlet 16 is provided at the rightward end of smaller diameter cylinder 18. The hydraulic pump 28 is driven by an electric motor 32 and includes an oil reservoir 30 connected by a line 29.

[0024] An inlet 17 is also provided to open into the smaller diameter cylinder 18. This inlet is connected to a line 11 connecting to the outlet 11A of the sphere 5. An electrically controlled solenoid valve 12 is included in the line 11. The outlet 16 of the smaller diameter cylinder 18 is connected to a line 15 which has an outlet 13 opening to the seawater surrounding the buoyancy control system. The line 15 includes a non-return valve 14.

[0025] The output surface of the smaller plate 20 has a surface area less than the input surface area of the larger plate 25 so that the pressure increase generated by the pressure multiplier is determined by the ratio of the surface areas of the output and input surfaces.

[0026] A battery 31 provides electrical power to a microprocessor controlled electronic control system 35 so that electrical power can be supplied to the electric motor 32 and the various electrically controlled solenoid valves.

[0027] A pressure transducer 36 is connected to the control system 35 to enable monitoring of the seawater pressure and hence the depth of the seawater. A further pressure

transducer 37 is connected to line 8 to monitor the internal pressure of the sphere 5.

[0028] The buoyancy control system of the present invention is provided to an apparatus such as an AUV. Prior to operation of the AUV, the battery 31 is fully charged, and the cylinder 10 is charged with a gas to the pressure GP, for example with air or an inert gas such as nitrogen or argon. The flexible bag 7 is extended with gas at below atmospheric pressure such that it substantially fills the internal space 6 of the sphere 5. The two part piston is located at its left extent and all solenoid valves are in their closed position. At this point, the AUV to which the buoyancy control system is attached is adjusted to be at neutral buoyancy.

[0029] In order to sink the AUV, negative buoyancy must be obtained. Thus, the control system 35 opens solenoid valve 4 so that seawater can travel along line 3 into the sphere 5. The water in the sphere 5 presses on the flexible bag 7 such that the volume of the flexible bag 7 decreases thereby producing negative buoyancy. The flexible bag 7 also functions to separate the gas therein from the seawater to prevent the gas dissolving into the seawater at high pressures.

[0030] As the AUV descends into the sea, the control system 35 monitors the depth via the pressure transducer 36 and provides further negative buoyancy as required by letting more seawater into the sphere 5 by controlling solenoid valve 4. At some point the required depth is reached, for example 3000 metres. At this point, the local pressure LP is 300 bar. If the rate of descent is too rapid, then the solenoid valve 9 can be opened to allow gas into the flexible bag 7 to cause it to expand thereby producing positive buoyancy. Thus, a stable descent of the AUV can be achieved.

[0031] When a positive buoyancy is actively required, i.e. the volume of seawater in the sphere 5 at local pressure LP must be decreased, the control system operates to open solenoid valve 9 such that gas from cylinder 10 can pass down line 8 to the flexible bag 7 as mentioned above. The pressure in the flexible bag 7 is substantially GP initially assuming that there is little volume within the bladder at local pressure LP. However, as the volume of the flexible bag 7 increases, the pressure GP will drop as the flexible bag 7 expands. At this time, the control system 35 can also open solenoid valve 12 which allows seawater from the sphere 5 to bleed down line 11 to the small cylinder 19 of the pressure multiplier 34. The solenoid valve 12 is then closed and electric motor 32 is activated to drive the hydraulic pump 28 to apply hydraulic pressure to the pressure multiplier 34, to drive the plates 25 and 20 in the rightward direction which applies an increased pressure to the seawater in volume 19. Thus, the seawater in volume 19 of the smaller cylinder 18 is emptied out of outlet 13 through line 15 and non return valve 14.

[0032] When the proximity switch 21 detects the rightward position of plate 25, the valve 12 is again opened to bleed seawater from sphere 5 into volume 19, this action forcing the pressure multiplier to return to its original position. When the proximity switch 26 detects that the plate 25 is in its leftward position, a signal is sent to the control system 35 which again causes the solenoid valve 12 to be shut and the cycle described above is repeated. That is to say, when the seawater has been expelled from the small cylinder 18, the electronic control system 35 can cause the pressure multiplier 34 to return to its original position and then re-cycle to expel more seawater from the sphere 5.

[0033] The pressure multiplier 34 is therefore preferably a

reciprocating pressure multiplier, in that it can reciprocate between a first position in which seawater can enter the volume 19 from the sphere 5, and a second position in which the seawater in the volume 19 has been expelled therefrom through outlet 16.

[0034] Thus, the pressure in the sphere 5 can be reduced allowing the flexible bag 7 to expand and create positive buoyancy. By using such a pressure multiplier 34, the electrical energy required to reduce the pressure in the sphere 5 is reduced. Moreover, by using cylinder 10 as a source of pressured gas, a pressure balancing can be achieved within the sphere wherein the amount of pumping work required to reduce the pressure of the seawater therein is reduced, which in turn reduces the amount of energy used by the electric motor 32. Figure 2 illustrates estimates of the energy required to generate buoyancy at 3000 metres depth using a pre-pressurised air cylinder of differing volumes at 300 bar. It will be appreciated that the pressure and volume of the cylinder 10 can therefore be selected to be most efficient at the particular depth at which the AUV will be working on its mission.

[0035] It will be appreciated that depending on the depth to which the AUV must descend during its mission, the cylinder gas pressure GP may be less than the seawater pressure LP at the maximum depth, and the volume of that cylinder may be varied as well.

[0036] As will be apparent to a person skilled in the art, the aforementioned advantageous energy saving effect using the cylinder 10 could also be achieved using a mechanical spring.

[0037] When a negative buoyancy is again required, i.e. the volume of seawater in the sphere at local pressure LP must be increased, the control system 35 will again open solenoid

valve 4 as above so that seawater can travel along line 3 into the sphere 5. The water in the sphere presses on the flexible bag 7 such that the volume of the bag decreases thereby producing negative buoyancy.

[0038] In this case, the variable load electrical generator 33 is driven to generate electricity during flow of seawater along the line 3 into the sphere 5. The control system 35 connects the electrical output of the generator 33 via an internal smoothing circuit (not shown) to produce a smoothed electrical signal suitable for application to an internal charging circuit (not shown) to distribute charging current to the battery 31 in accordance with need, as monitored by the control system 35.

[0039] Consequently, when negative buoyancy is required, some of the energy expended to achieve positive buoyancy is regenerated or recovered. Since the flow rates along line 3 will vary, the generator 33 preferably includes a system whereby the load can be dynamically changed to generate the optimum efficiency. The generator is in effect a regenerative pump and when there is a large pressure differential across the regenerative pump, the load (battery charging intensity) can be set very high as there is a lot of energy available to operate the regenerative pump (i.e. it should be harder to operate it at high charging intensities than at low intensities). Conversely, at low pressure differentials, the charging intensity should be set to be low to enable the regenerative pump to still operate.

[0040] Preferably, the variable load regenerative pump should be able to dynamically alter the load characteristic depending on the constantly changing pressure differential between LP and the pressure in the sphere 5 during the mission. It will be appreciated that a microprocessor controlled control system 35 can do this.

[0041] It will be appreciated that the above described operations for achieving negative and positive buoyancy may be achieved either by pre-programming the control system 35, by the electronic control system 35 responding to signals sent by a controller at a home station, or automatically in response to external conditions (for example, depth data from a depth gauge).

[0042] The present invention can thus provide a buoyancy control system which can enable a buoyancy change of 34 kg at 6000 metres with a low power consumption (24V battery, 150W electric motor). Moreover, the system is relatively lightweight and compact, which in turn allows it to be used as a "bolt-on" to existing underwater submersibles.

[0043] It will be understood that the embodiment illustrated shows one application of the invention only for the purposes of illustration. In practice the invention may be applied to many different configurations, the detailed embodiments being straightforward for those skilled in the art to implement.